Strange Resonance Production: Probing Chemical and Thermal Freeze-out in Relativistic Heavy Ion Collisions

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The production and the observability of $\Lambda(1520)$, $K^0(892)$ Φ and $\Delta(1232)$ hadron resonances in central Pb+Pb collisions at 160 AGeV is addressed. The rescattering probabilities of the resonance decay products in the evolution are studied. Strong changes in the reconstructable particle yields and spectra between chemical and thermal freeze-out are estimated. Abundances and spectra of reconstructable resonances are predicted.

Strange particle yields and spectra are key probes to study excited nuclear matter and to detect the transition of (confined) hadronic matter to quark-gluon-matter (QGP) [1–8]. The relative enhancement of strange and multi-strange hadrons, as well as hadron ratios in central heavy ion collisions with respect to peripheral or proton induced interactions have been suggested as a signature for the transient existence of a QGP-phase [1].

Unfortunately, the emerging final state particles remember relatively little about their primordial source, since they had been subject to many rescatterings in the hadronic gas stage [9–11]. This has given rise to the interpretation of hadron production in terms of thermal/statistical models. Two different kinds of freeze-outs are assumed in these approaches:

1. a chemical freeze-out, were the inelastic flavor changing collisions processes cease, roughly at an energy per particle of 1 GeV [12],

2. followed by a later kinetic/thermal freeze-out were also elastic processes have come to an end and the system decouples.

Chemical and thermal freeze-out happen sequentially at different temperatures ($T_{\rm ch} \approx 160-170$ MeV, $T_{\rm th} \approx 120$ MeV) and thus at different times.

To investigate the sequential freeze-out in heavy ion reactions at SPS the Ultra-relativistic Quantum Molecular Dynamics model (UrQMD 1.2) is applied [13,14]. UrQMD is a microscopic transport approach based on the covariant propagation of constituent quarks and diquarks accompanied by mesonic and baryonic degrees of freedom. It simulates multiple interactions of ingoing and newly produced particles, the excitation and fragmentation of color strings and the formation and decay of hadronic resonances. At present energies, the treatment of sub-hadronic degrees of freedom is of major importance. In the UrQMD model, these degrees of freedom enter via the introduction of a formation time for hadrons produced in the fragmentation of strings [15–17]. The leading hadrons of the fragmenting strings contain the valence-quarks of the original excited hadron. In UrQMD they are allowed to interact even during their formation time, with a reduced cross section defined by the additive quark model, thus accounting for the original valence quarks contained in that hadron [13,14]. Those leading hadrons therefore represent a simplified picture of the leading (di)quarks of the fragmenting string. Newly produced (di)quarks do, in the present model, not interact until they have coalesced into hadrons – however, they contribute to the energy density of the system. For further details about the UrQMD model, the reader is referred to Ref. [13,14].

Let us start by asking whether a microscopic non-equilibrium model can support the ideas of sequential chemical and thermal break-up of the hot and dense matter? To analyze the different stages of a heavy ion collision, Fig. 1 shows the time evolution of the elastic and inelastic collision rates in Pb+Pb at 160AGeV. The inelastic collision rate (full line) is defined as the number of collisions with flavor changing processes (e.g. $\pi\pi \to K\overline{K}$). The elastic collision rate (dashed dotted line) consists of two components, true elastic processes (e.g. $\pi\pi \to \pi\pi$) and pseudo-elastic processes (e.g. $\pi\pi \to \rho \to \pi\pi$). While elastic collision do not change flavor, pseudo-elastic collisions are different. Here, the ingoing hadrons are destroyed and a resonance is formed. If this resonance decays later into the same flavors as its parent hadrons, this scattering is pseudo-elastic.

Indeed the main features revealed by the present microscopic study do not contradict the idea of a chemical and thermal break-up of the source as shown in Fig. 1 (top) However, the detailed freeze-out dynamics is much richer and by far more complicated as expected in simplified models:

1. In the early non-equilibrium stage of the AA collision ($t < 2$ fm/c) the collision rates are huge and vary strongly with time.

2. The intermediate stage (2 fm/c$< t < 6$ fm/c) is dominated by inelastic, flavor and chemistry changing processes until chemical freeze-out.

3. This regime is followed by a phase of dominance of elastic and pseudo-elastic collisions (6 fm/c$< t <$ 11 fm/c). Here only the momenta of the hadrons change, but the chemistry of the system is mainly

unaltered, leading to the thermal freeze-out of the system.

Finally the system breaks-up ($t > 11$ fm/c) and the scattering rates drop exponentially.

Fig. 1 (bottom) depicts the average energy[1] per particle at midrapidity ($|y - y_{\rm cm}| \leq 0.1$). One clearly observes a correlation between chemical break-up in terms of inelastic scattering rates and the rapid decrease in energy per particle. Thus, the suggested phenomenological chemical freeze-out condition of ≈ 1 GeV/particle is also found in the present microscopic model analysis.

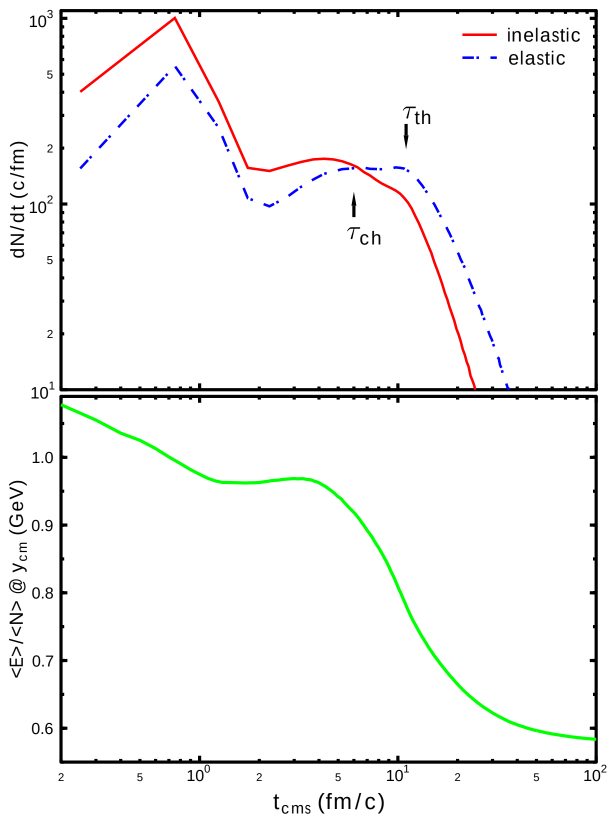

FIG. 1. Top:Inelastic and (pseudo-)elastic collision rates in Pb+Pb at 160AGeV. $\tau_{\rm ch}$ and $\tau_{\rm th}$ denote the chemical and thermal/kinetic freeze-out as given by the microscopic reaction dynamics of UrQMD. Bottom: Average energy per particle at midrapidity ($|y - y_{\rm cm}| \leq 0.1$) as a function of time.

To verify this scenario, we exploit the spectra and abundances of $\Lambda(1520)$, $K^0(892)$ and other resonances which unravel the break-up dynamics of the source between chemical and thermal freeze-out. In the statistical model interpretation of heavy ion reactions the resonances are produced at chemical freeze-out. If chemical and thermal freeze-out are not separated - e.g. due to an explosive break-up of the source - all initially produced resonances are reconstructable by an invariant mass analysis in the final state. However, if there is a separation between the different freeze-outs, a part of the resonance daughters rescatter, making this resonance unobservable in the final state. Thus, the relative suppression of resonances in the final state compared to those expected from thermal estimates provides a chronometer for the time period between the different reaction stages. Even more interesting, inelastic scatterings of the resonance daughters (e.g. $\overline{K}p \rightarrow \Lambda$) might change the chemical composition of the system *after* 'chemical' freeze-out by as much as 10% for all hyperon species. While this is not in line with the thermal/statistical model interpretation, it supports the more complex freeze-out dynamics encountered in the present model.

To answer these questions we address the experimentally accessible hadron resonances: At this time Φ and $\Lambda(1520)$ have been observed in heavy ion reactions at SPS energies [18,19] following a suggestion that such a measurement was possible [20]. SPS [19] and RHIC experiments [21] report measurement of the $\overline{K^0}(892)$ signal, and RHIC has already measured both the K^0 and the $\overline{K^0}$. In the SPS case, the $\Lambda(1520)$ abundance yield is about 2.5 times smaller than expectations based on the yield extrapolated from nucleon-nucleon reactions. This is of highest interest in view of the Λ enhancement by factor 2.5 of in the same reaction compared to elementary collisions.

As an explanation for this effective suppression by a factor 5, we show that the decay products (π, Λ, etc.) produced at rather high chemical freeze-out temperatures and densities have rescattered. Thus, their momenta do not allow to reconstruct these states in an invariant mass analysis. However, even the question of the existence of such resonance states in the hot and dense environment is still not unambiguously answered. Since hyperon resonances are expected to dissolve at high energy densities (see .e.g. [22]) it is of utmost importance to study the cross section of hyperon resonances as a thermometer of the collision.

The present exploration considers the resonances, $\Delta(1232)$, $\Lambda^*(1520)$, $K^0(892)$ and Φ. The properties of these hadrons are depicted in Table I.

Particle	Mass (MeV)	Width (MeV)	τ (fm/c)
$\Delta(1232)$	1232	120	1.6
$\Lambda^*(1520)$	1520	16	12
$K^0(892)$	893	50	3.9
$\Phi(1020)$	1019	4.43	44.5

TABLE I. Properties of investigated resonances.

[1]To compare to thermal model estimates, the energies are calculated from interacted hadrons with the assumption $p_z^2 = \left(p_x^2 + p_y^2\right)/2$. This assures independence of the longitudinal motion in the system and the chosen rapidity cut.

Fig. 2 shows the rapidity densities for $\Delta(1232)$, $\Lambda^*(1520)$, $\mathrm{K}^0(892)$ and Φ in Pb(160 AGeV)Pb, b< 3.4 fm collisions. Fig. 2 (left), shows the total amount of decaying resonances. Here, subsequent collisions of the decay products have not been taken into account - i.e. whenever a resonance decays during the systems evolution it is counted. However, the additional interaction of the daughter hadrons disturbs the signal of the resonance in the invariant mass spectra. This lowers the observable yield of resonances drastically as compared to the primordial yields at chemical freeze-out. Fig. 2(right) addresses this in the rapidity distribution of those resonances whose decay products do not suffer subsequent collisions - these resonances are in principle reconstructable from their decay products. Note that reconstructable in this context still assumes reconstruction of all decay channels, including many body decays.

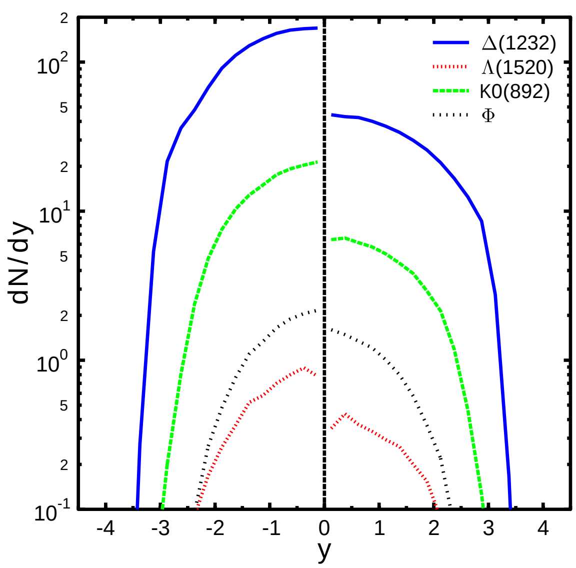

FIG. 2. Rapidity densities for $\Delta(1232)$, $\Lambda^*(1520)$, $\mathrm{K}^0(892)$ and Φ in Pb(160 AGeV)Pb, b< 3.4 fm collisions. Left: All resonances as they decay. Right: Reconstructable resonances.

At SPS energies, the rapidity distributions $\mathrm{d}N/\mathrm{d}y$ may by described by a Gaussian curve

$$\frac{\mathrm{d}N}{\mathrm{d}y}(y) = A \times \exp\left(-\frac{y^2}{2\sigma^2}\right) \quad . \tag{1}$$

with parameters given in Table II. However, in this approximation the details of the rapidity distributions are lost. Especially the dip in the rapidity distributions of the $\Lambda(1520)$ is not accounted for.

The rescattering probability of the resonance decay products depends on the cross section of the decay product with the surrounding matter, on the lifetime of the surrounding hot and dense matter, on the lifetime of the resonance and on the specific properties of the daughter hadrons in the resonance decay channels. This leads to different 'observabilities' of the different resonances: Rescattering influences the observable Φ and Λ^* yields only by a factor of two, due to the long life time of those particles. In contrast strong effects are observed in the K^* and Δ yields, which are suppressed by more than a factor three.

One can use the estimates done by [23] in a statistical model, and try to relate the result of the present microscopic transport calculation to thermal freeze-out parameters. The ratios of the 4π numbers of reconstructable is $\Lambda(1520)/\Lambda = 0.024$ and $\mathrm{K}^0(892)/\mathrm{K}^+ = 0.25$. In terms of the analysis by [23], the microscopic source has a lifetime below 1 fm/c and a freeze-out temperature below 100 MeV. Thus, the values obtained from UrQMD seem to favor a scenario of a sudden break-up of the initial hadron source, in contrast to the time evolution of the chemical and thermal decoupling as shown in Fig. 1. However, note that these numbers are based on the above mentioned thermal scenario. In fact, fitting hadron ratios of UrQMD calculations for central Pb+Pb interactions at 160 AGeV with a Grand Canonical ensemble yields a chemical freeze-out temperature of $150 - 160$ MeV [24].

In fact, the rescattering strength depends on the phase space region studied. Fig. 3 addresses the longitudinal momentum distribution of the rescattering strength. The probability R to observe the resonance H is given by

$$R = \frac{H \to h_1 h_2(\text{reconstructable})}{H \to h_1 h_2(\text{all})} \quad . \tag{2}$$

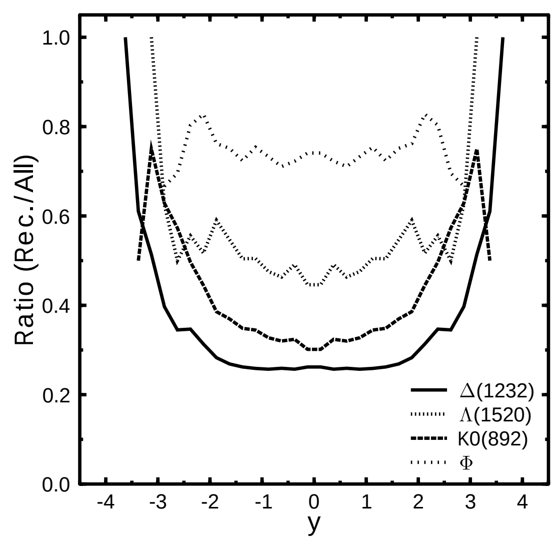

FIG. 3. Rapidity dependent ratio R of reconstructable resonances over all resonances of a given type as they decay. For $\Delta(1232)$, $\Lambda^*(1520)$, $\mathrm{K}^0(892)$ and Φ in Pb(160 AGeV)+Pb, b< 3.4 fm collisions.

The 'observability' decreases strongly towards central rapidities. This is due to the higher hadron density at central rapidities which increases the absorption probability of daughter hadrons drastically. Unfortunately, in the case of the Φ meson this decrease of the observable yield increases the discrepancies between data and microscopic model predictions (e.g. [2]).

The absorption probability of daughter hadrons is not only rapidity dependent but also transverse momentum dependent. The decay products are rescattered preferentially at low transverse momenta. Fig. 4 depicts the invariant transverse momentum spectra of reconstructable Δ(1232), Λ*(1520), K^0(892) and Φ in Pb(160 AGeV)Pb, b< 3.4 fm collisions.

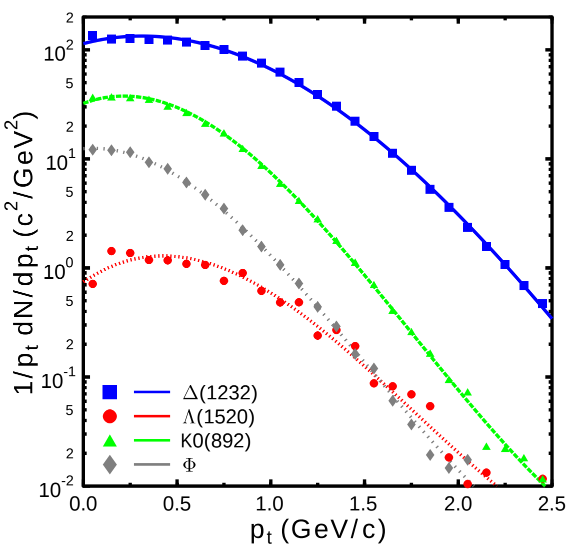

FIG. 4. Transverse momentum spectra at $|y - y_{\rm cm}| < 1$ of reconstructable resonances for Δ(1232), Λ*(1520), K^0(892) and Φ in Pb(160 AGeV)Pb, b< 3.4 fm collisions. The lines are to guide the eye.

Particle (All)	A	σ
Δ	181	1.49
Λ*	0.89	1.20
K*	22.0	1.23
Φ	2.22	1.09
Particle (Rec.)	A	σ
Δ	46.3	1.60
Λ*	0.42	1.27
K*	6.95	1.34
Φ	1.62	1.10

TABLE II. Gaussian fit parameters for the rapidity densities of all and reconstructable resonances.

Fig. 5 directly addresses the p_t dependence of the observability of resonances. The present model study supports a strong p_t dependence of the rescattering probability. This effects leads to a larger apparent temperature (larger inverse slope parameter) for resonances reconstructed from strongly interacting particle. A similar behavior has been found for the Φ meson in an independent study by [25]. This effective heating of the Φ spectrum might explain the different inverse slope parameter measured by NA49 ($\phi \rightarrow K^+K^-$) as compared to the NA50 ($\phi \rightarrow \mu^+\mu^-$) collaboration [2,25,7,26].

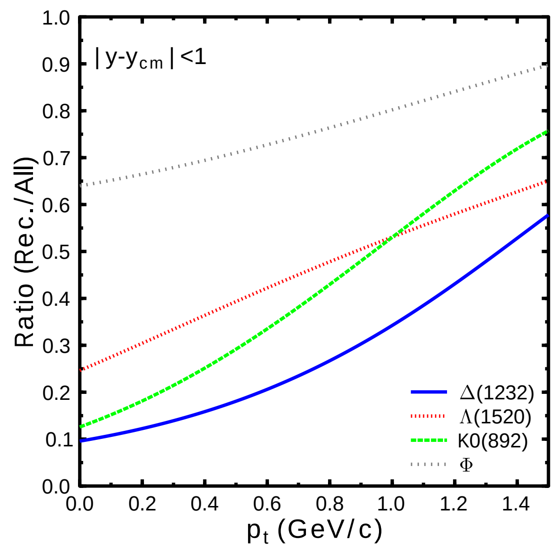

FIG. 5. Ratio R of reconstructable resonances over all resonances of a given type as a function of transverse momentum. For Δ(1232), Λ*(1520), K^0(892) and Φ in Pb(160 AGeV)Pb, b< 3.4 fm collisions.

In conclusion, central Pb+Pb interactions at 160 AGeV are studied within a microscopic non-equilibrium approach. The calculated scattering rates exhibit signs of a chemical and a subsequent thermal freeze-out. The time difference between both freeze-outs is explored with hadronic resonances. The rapidity and transverse momentum distributions of strange and non-strange resonances are predicted. The observability of unstable (strange) particles (Λ(1520), ϕ, etc.) in the invariant mass analysis of strongly interacting decay products is distorted due to rescattering of decay products from chemical to thermal freeze-out. Approximately 25% of ϕ's and 50% of Λ*'s are not directly detectable by reconstruction of the invariant mass spectrum. The rescattering strength is strongly rapidity dependent. Rescattering of the decay products alters the transverse momentum spectra of reconstructed resonances. This leads to higher apparent temperatures for resonances. Inelastic collisions of anti-Kaons from decayed strange resonance alter the chemical composition of strange baryons by up to 10%.

events	1400
Δ/event	654.46
Λ^*/event	2.60
$K^0(892)$/event	66.2
Φ/event	5.917

TABLE III. 4π yields of all decaying resonances in Pb(160AGeV)+Pb, b< 3.4 fm.

events	1400
Δ/event	178.9
Λ^*/event	1.28
$K^0(892)$/event	22.61
Φ/event	4.35

TABLE V. 4π yields of all reconstructable resonances in Pb(160AGeV)+Pb, b< 3.4 fm.

y	dn/dy(Δ)	dn/dy(Λ(1520))	dn/dy(K^0(892))	dn/dy(Φ)
0.125	169.12	0.78	21.36	2.16
0.375	167.40	0.89	20.36	2.05
0.625	163.89	0.79	19.20	1.89
0.875	155.86	0.7	17.56	1.65
1.125	143.33	0.58	14.99	1.33
1.375	128.78	0.52	12.83	1.10
1.625	110.98	0.36	10.31	0.76
1.875	90.976	0.26	7.554	0.48
2.125	67.511	0.16	4.815	0.26
2.375	47.786	0.09	2.378	0.09
2.625	36.04	0.03	0.802	0.03
2.875	21.583	0.01	0.2	0.00
3.125	5.3613	0.00	0.028	0
3.375	0.2719	0	0.00	0
3.625	0.0017	0	0	0
3.875	0	0	0	0

TABLE IV. Rapidity density of all decaying resonances in Pb(160AGeV)+Pb, b< 3.4 fm.

y	dn/dy(Δ)	dn/dy(Λ(1520))	dn/dy(K^0(892))	dn/dy(Φ)
0.125	44.30	0.348	6.44	1.601
0.375	43.03	0.437	6.59	1.484
0.625	42.46	0.37	6.14	1.342
0.875	40.05	0.332	5.75	1.21
1.125	37.08	0.292	5.16	1.008
1.375	33.74	0.262	4.47	0.797
1.625	29.82	0.200	3.81	0.579
1.875	25.72	0.154	2.91	0.361
2.125	21.14	0.087	2.14	0.22
2.375	16.57	0.050	1.18	0.0752
2.625	12.43	0.018	0.46	0.022
2.875	8.570	0.007	0.12	0.002
3.125	2.755	0.001	0.02	0
3.375	0.165	0	0.00	0
3.625	0.001	0	0	0
3.875	0	0	0	0

TABLE VI. Rapidity density of reconstructable resonances in Pb(160AGeV)+Pb, b< 3.4 fm.

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